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# Tuning the Assembling Process of Modules by the Use of Proper Equipment

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**Abstract.** The tuning of the assembly line of concentrated photovoltaic (CPV) modules is an important task to ensure that the efficiency of modules made at the production line is as high as those fabricated in the development phase. A solar simulator for CPV and a module optical analyzer (MOA) are proposed to be used in production to improve the quality of the assembling process (both during the tuning of the production line and once it is completed). Moreover, the usefulness of performing a quality control based on maximum power and optical pointing of modules is discussed by performing a deep analysis of some modules manufactured in the production line and characterized both indoors and outdoors.

## INTRODUCTION

The work presented in this document has been carried out within the European project ECOSOLE which has received funding from the European Union's Seventh Framework Program under grant agreement n° 295985. The main objective of the project ECOSOLE (Elevated Concentration photovoltaic SOLar Energy generator and fully automated machinery for high throughput manufacturing and testing) is to provide efficient and cheap energy generator based on CPV technology, while promoting collaboration and cooperation among European universities (and BGU University, Israel) and industrial companies. During this project, a CPV module, an inverter and a tracker have been designed and manufactured together with an automatic high precision assembly line of modules. Regarding this second task, the project coordinator BECAR (Italy) realized the CPV module assembly line and the Universidad Politécnica de Madrid (UPM, Spain) developed and installed quality control equipment at the module assembly line.

This article discusses the usefulness of performing some kind of quality control in production, in particular to measure the maximum power of modules and the optical pointing (defined as the average value of the misalignments between the optical system-cell units comprising the module). Firstly, a brief description of the developed equipment for indoor module testing is presented at the beginning of the text. Also, the role of this instrumentation in the tuning of the production line will be discussed. Secondly, the article includes a deep analysis of the indoor and outdoor characterization of some modules manufactured in the assembling line before being installed in a tracker. The objective of this analysis is to confirm if the information gathered during the indoor quality control can be related to the outdoor performance of modules. With this study is possible to answer some questions, as for example, if the relative performance of the modules in terms of generated power is the same for both indoors and outdoors, or for example, if the installation procedure of modules in the tracker varies significantly the pointing measured indoors, and consequently the module performance.

## QUALITY CONTROL AT THE ASSEMBLING LINE

The efficiency of modules manufactured at the production line must reach efficiency values as high as those fabricated in the development phase. In this regard, the developed module hand-made before the whole automatization of the assembling is a good starting point to define the minimum desired quality in production. The machines designed for high speed production offer more accuracy and reliability than human counterparts. However, a fine tuning of the assembling process is essential to reach acceptable results.

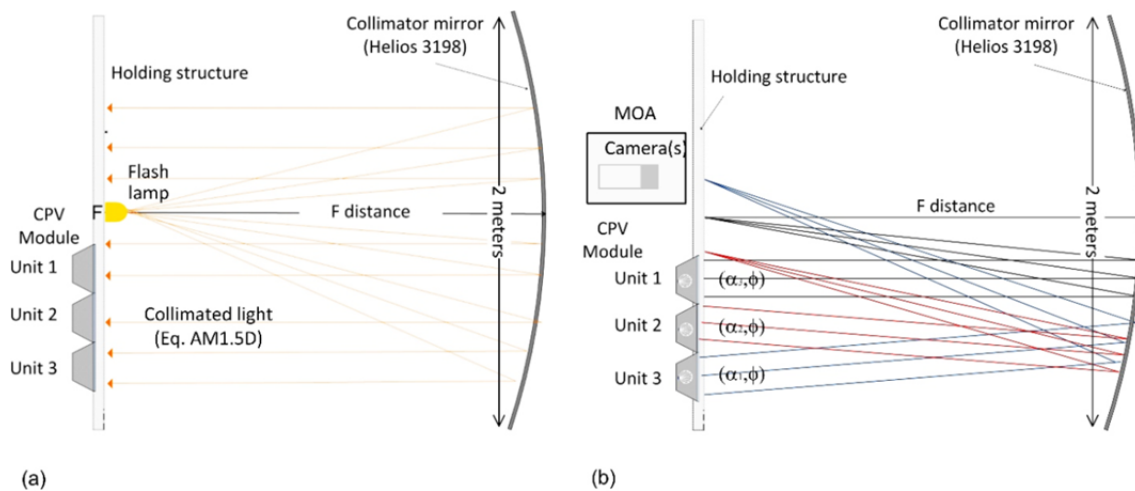
Tuning of the assembly line may be a difficult task due to the large number of processes involved in the module manufacturing. There are different key points related to these processes that affect the module quality and thus reduce its efficiency, for example, the process of adhering the secondary optical element (SOE) to the cell, the positioning of the receivers on the back plate [1], or the sealing of the parquet of primary optical elements (POEs) to the module chassis [2]. All these sources of errors could be investigated by complicated simulations if several aspects and properties of the assembling process and module components are known. Nevertheless, important parameters, such as the misalignment of each SOE over each cell, or the warping of the lens parquet when fixed to the module housing, may be unknown.

In the ECOSOLE project, an indoor module testing based on a solar simulator for CPV to measure the maximum power and a module optical analyzer (MOA) to obtain the optical pointing have been developed.

### Solar Simulator Helios 3198 and Module Optical Analyzer (MOA)

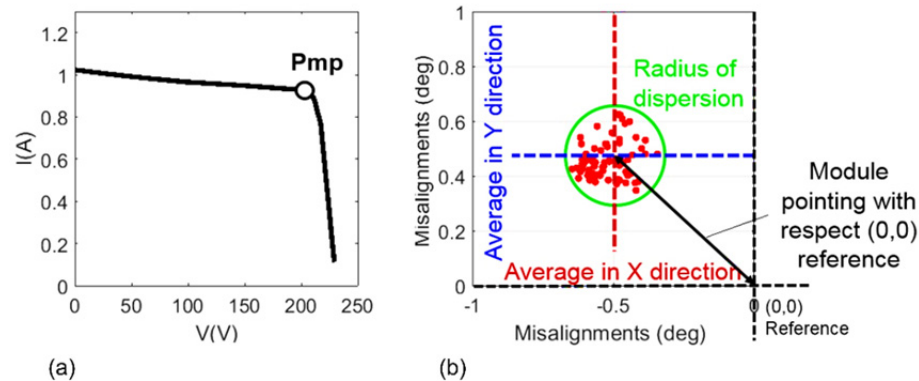
The solar simulator for CPV modules Helios 3198 [3] provides collimated ( $\pm 0.43^\circ$ ) and uniform light ( $\pm 5\%$  measured with a 3 cm x 3 cm lens of  $\pm 1^\circ$  acceptance angle) with equivalent spectrum AM1.5D ( $SMR_{top-middle}=1$ ) in a circular area of 2 meters of diameter. The simulator light system is based on a 2 meters diameter parabolic mirror and a Xenon lamp placed at its focus [FIGURE 1(a)].

The Module Optical Analyzer (MOA) has been developed by UPM to implement the Luminescence-Inverse (LI) method [4,5]. The LI method is proposed to measure the optical-angular properties of CPV modules, with large CPV aperture areas and in static mode, based on the reverse optical path (i.e., the module is forward biased at dark conditions to emit light). The 2 meters diameter collimator of the solar simulator is used to focus the backward light (radiated from the module) with a given angular direction ( $\alpha, \phi$ ) to the same point in the focal plane of the mirror. The MOA (that is placed at the focal plane of the collimator) consists of a set of cameras [FIGURE 1 (b)]. Each camera (located at a given position in the focal plane of the mirror) takes an image of the light emitted by the module with a particular angular direction ( $\alpha, \phi$ ). The angular transmittance function  $T(\alpha, \phi)$  (and the angular acceptance) of every optical system-cell unit in the module can be obtained based on these images in a short period of time, if plotting the integration of pixels values related to each unit in the image as function of the angular direction ( $\alpha, \phi$ ).



**FIGURE 1.** Measurement scheme at the Helios 3198 solar simulator to measure (a) the electrical properties (IV curve) by direct illumination at the module aperture with a Xenon lamp at the focus of the mirror, (b) the optical-angular properties (angular transmittance function) by the MOA placed at focus of the collimator following the luminescence-inverse (LI) method.

The maximum power (Pmp) of the module is obtained at the solar simulator once the whole IV curve is measured [FIGURE 2 (a)]. The misalignment (angular pointing) of each unit in the module and the radius of dispersion of the misalignment distribution (of all units) can be obtained from the angular transmittance functions (of all the optical system-cell units comprising the module) measured by MOA. The module pointing defined as the average of the units misalignments is calculated with respect to a given constant reference [FIGURE 2 (b)]. It is important to stand out that this reference must be kept constant for all measurements and that its absolute value is related to the calibration of the MOA. The quality control performed in the production line is based on Pmp, radius of dispersion and module pointing (given by the two coordinates: average misalignment in X direction and average misalignment in Y direction).

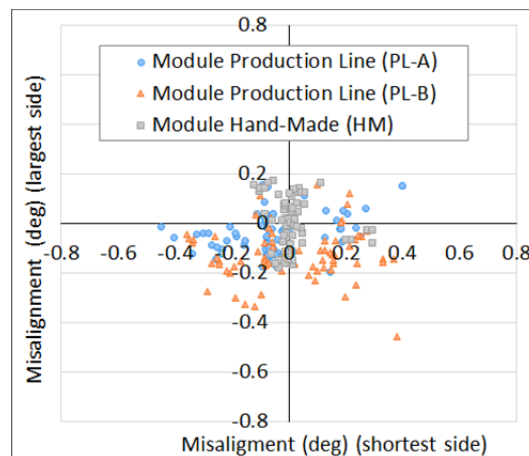


**FIGURE 2.** The quality control performed in the production line is based on (a) Pmp measured at the solar simulator, (b) radius of misalignments dispersion and pointing of the module.

### Tuning the Assembly Line of BECAR Modules

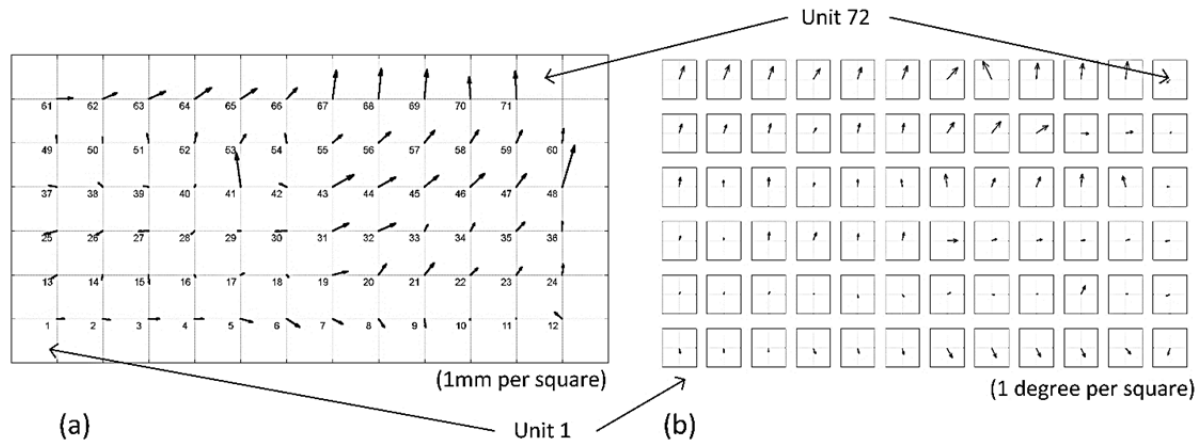
During the tuning of the assembly line, the measurements performed in the solar simulator and in the MOA, both installed in the assembly line, have been very helpful to improve the manufacturing process. The source of error in the production line may be investigated based on the MOA results among other things. This is possible because the pattern of the misalignments in the module can be directly related to different failures during the assembling process. To illustrate this, we can compare the performance of two first modules manufactured at the production line PL-A and PL-B (randomly selected) during the first steps of the tuning of the assembling process (before the line was completed and optimized) and one module hand-made HM (considered the “perfect” module in terms of assembling process, as the standard deviation of misalignments is lower than 20% of the design acceptance angle which has been proven to be an acceptable value for module on production).

The BECAR module dimension is 1000mm X 550 mm approximately and consists of 72 units series connected with each unit formed by a Silicone-on-Glass Fresnel lens aligned with a receiver based on an inverted dielectric pyramid and a 3-junction solar cell.



**FIGURE 3.** Misalignments of three different modules

In FIGURE 3, for the modules made in production (before the line was completed and optimized), most of the misalignments are within  $\pm 0.4$  degrees with larger values in the shortest side of module. In principle, these larger values in the shorter side are strange as the largest misalignments are expected in the longest side (higher accumulative shift due to wrong positioning and bending). This is the case for the module HM in which most of the misalignments are within  $\pm 0.2$  degrees for Y direction. This narrow misalignment distribution that has no dependence with the position of the unit in the module, confirms that (for this particular module) the effect of bending in the lens parquet is an order of magnitude lower than the effect of bad positioning of the receivers in the back plate. This is also confirmed by comparing the exact position of the receivers in the back plane of some manufactured modules in production (found using time consuming and tedious measurements by coordinate measuring machine CMM) with the MOA results. The pattern given by these positions was consistent with the misalignments measured by the MOA [FIGURE 4].



**FIGURE 4.** (a) Position of the 72 receivers in the back plane of a module made in production before the assembling line was completed and optimized (known by CMM measurements); (b) Misalignments of units in a module made in production before the assembling line was completed and optimized (measured by MOA). Results are related to two different modules made in production.

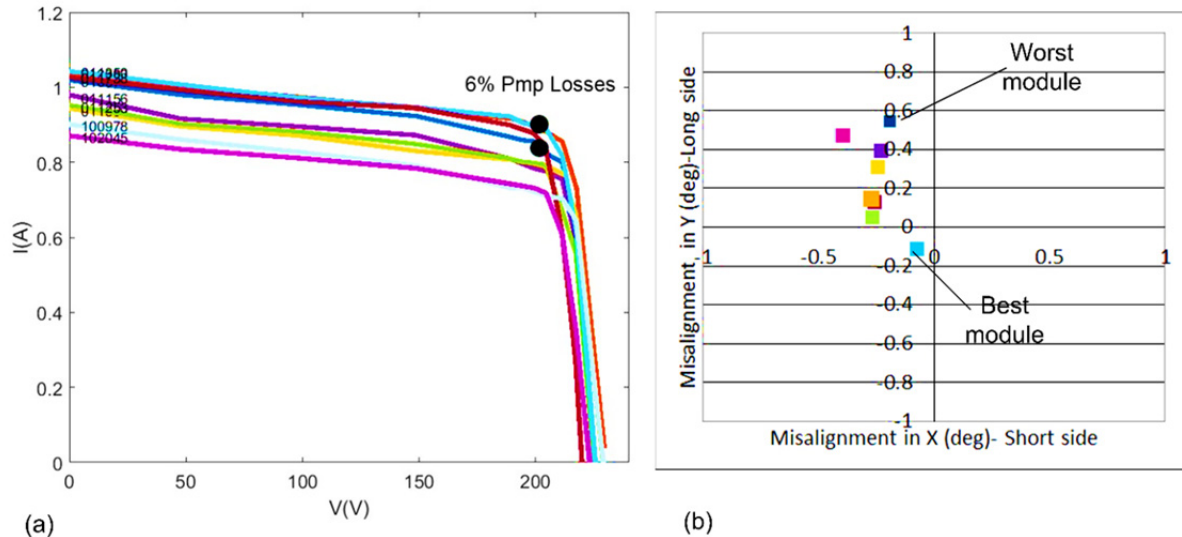
From this data, we can make two main conclusions. First, that the incorrect positioning of receivers during the evaluated step of the tuning phase seems to be the largest source of misalignments (more so than bending of lenses) and second, that the MOA equipment can be very useful to reshape the production line and control the quality of manufactured modules.

## INDOOR VS. OUTDOOR PERFORMANCE OF MODULES

This section includes a deep analysis of the indoor and outdoor characterization of 9 modules randomly selected that have been manufactured in the assembling line. The objective of this analysis is to confirm first, if there is a relation between solar simulator and MOA measurements, and second, if the information gathered during the indoor quality control can be extended to the outdoor performance of modules. With this study is possible to evaluate if the relative performance of the modules keeps constant from outdoor to indoor or on the contrary, for example, the installation procedure of modules in the tracker varies significantly the module performance.

### Indoor Characterization

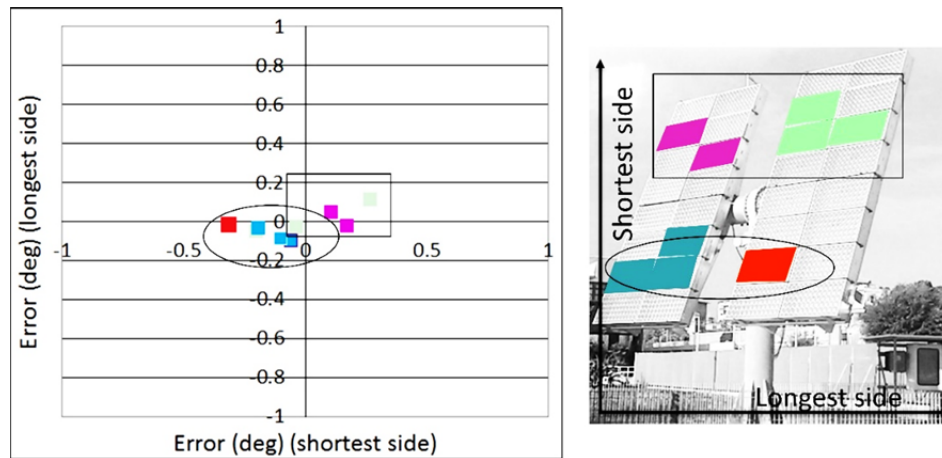
FIGURE 5 presents the IV curves and the pointing of the 9 randomly selected modules measured by the solar simulator and the MOA after being manufactured in the production line. There are clear differences between short circuit current within these IV curves. The reason is that the modules have been manufactured following three designs that differs only in the distance from the Fresnel lens to the receiver ( $\pm 3\%$  of variation from the optimum). For that reason, only the modules with the same focal distance are compared in Pmp and pointing. For the group of modules that has the same focal distance and the best performance, if the best module and worst module are compared, losses of 6% in Pmp are observed for a pointing difference of 0.6 degrees as presented in FIGURE 5.



**FIGURE 5.** Indoor characterization of 9 (randomly selected) CPV modules manufactured in the production line: (a) I-V curves measured at the solar simulator, (b) modules pointing measured by MOA.

### Indoor Vs. Outdoor Characterization

A first prototype of BECAR CPV system has been realized during the ECOSOLE project. The system is formed by 32 CPV modules being 9 of them the selected modules under study (FIGURE 6). Each module has its own inverter, thus the angular transmittance function of each module can be measured while stopping the tracker and biasing the module at its Pmp. The pointing of each module installed at the tracker were therefore measured and compared with the values measured by MOA in the production line. FIGURE 6 shows the error between pointing of 9 selected modules measured by MOA in the production line and the pointing measured after being installed in the tracker. It can be observed that these errors are larger for the direction coincident with the shortest side of the module.



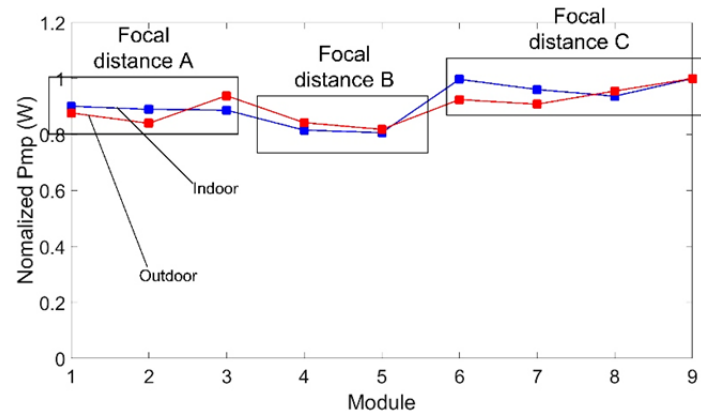
**FIGURE 6.** Error between pointing of 9 selected modules measured by MOA in the production line and the pointing measured after being installed in the tracker (indoor vs. outdoor).

These calculated errors can be related with the position of each module in the tracker as presented in FIGURE 6. The error in pointing (indoor vs. outdoor) is positive in the direction coincident with the shortest side of the module for those at the upper part of the tracker (modules inside the square in FIGURE 6). Contrary, the error pointing is negative in the direction coincident with the shortest side of the module for those at the lower part of the tracker (modules inside the circle in FIGURE 6). If the pointing of modules is assumed to keep constant from indoor to



outdoor conditions (including installation in the tracker), this comparison reveals a minimum bending of the tracker that produces differences up to 0.25 degrees.

FIGURE 7 presents the normalized Pmp of the 9 selected modules measured indoors in the solar simulator and outdoors at the tracker during a clear sunny day. In this comparison, the “perfect” module in terms of assembling process presented in previous section is not considered for being a reference because it was handmade and not installed in a tracker. The main objective of this relative comparison is to observe how critical the alignment of modules is outdoors. The relative performance between these modules seems to be very similar for both indoor and outdoor but unfortunately there is not enough data to confirm this performance at different ambient conditions (i.e., spectrum and temperature). Nevertheless, differences of performance between modules seem to be governed by the focal distance value of the module more than any other effect [6,7], as for example, the observed errors in pointing due to a possible bending of the tracker.



**FIGURE 7.** Normalized Pmp of selected 9 modules measured indoors at the solar simulator and outdoors at the tracker. The investigated 9 modules can be sorted by their lens-to-cell distances (there are 3 different values).

## CONCLUSIONS

For the case under study (BECAR technology developed during the ECOSOLE project), we can summarize some conclusions regarding the indoor quality control in production line:

Misalignments measured by MOA reveals faulty modules in production (pointing is linked with Pmp), for example, losses of 6% in Pmp have been observed for pointing values of 0.6 degrees.

Differences of 0.25 degrees in the module pointing at indoor and outdoor have been observed and assumed to be caused by tracker bending. Nevertheless, these differences in pointing seem not to affect the relative indoor/outdoor performance (Pmp) among modules. Variations of lens-to-cell distance have been confirmed to produce differences on Pmp of about 16% (indoor measurements) and 12% (outdoor measurements) for  $\pm 3\%$  of distance variation with respect to the optimum distance.

## ACKNOWLEDGEMENTS

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